Bond Structure and Tensile Properties of Thermal Bonded Polypropylene Nonwovens

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Abstract

Extensive studies have been conducted to investigate the effect of several process conditions on the structure and properties of nonwoven webs. As thermal point bonding is one of the most important processes, a detailed analysis of the point bond structures was done to help understand the development of tensile properties. Spunbond fabrics produced under different conditions were investigated, especially with respect to bond structure and failure mechanisms. Although bond structure does not show a big difference on microscopic observation, the way it responds during tensile deformation is dissimilar depending on the bonding temperature, leading to differences in failure mechanisms and tensile properties of the web.

Keywords

Spunbonding; Bond Structure; Nonwovens; Thermal Bonding; Polypropylene; Calendering; Tensile Properties

Background

Spunbonding is one of the most widely used methods to produce nonwovens contributing to more than 45% of the produced nonwovens [INDA, 2007]. In this process the molten polymer is forced through a block of spinnerets to produce a curtain of filaments. The air ducts force airs through the spinning chamber at high speed, and meanwhile the filaments are drawn by the air drag and then continuously cooled. The drawn filaments then pass through a venturi which is a high-velocity-low-pressure zone and a distributing chamber. This causes the filaments to fan out and randomize, which is then laid on a moving collector belt. The random web of filaments is then strengthened by bonding [Bhat and Malkan, 2002]. Thermal point bonding is mostly employed for webs of low to medium basis weight [Dharmadhikary et al, 1995].

Effect of various processing conditions on the structure and properties of filaments and the bonded webs has been extensively studied [Chand et , 2001 and 2002, Fedorova and Purdeyhimi, 2007, Kim et al 2002, Malkan et al, 1992, Michielsen et al 2006, Rwei et al, 2004, Zhang et al, 1998]. Thermal bonding of the filaments is an inherent part of the process and is affected by the varying spinning conditions. Thermal point bonding utilizes temperature, pressure (what about time?) and time to affect fiber-to-fiber fusion. It is more flexible, since lower melting fibers or segments are not required in the web. Point bonding is usually accomplished by passing a consolidated web through heated nip rolls, one of which is embossed. Bonding temperatures for polypropylene usually do not exceed 170°C, but pressures on the raised points are between 138 and 310 MPa. The bonding between the points can be controlled by adjusting the ratio of the heights of the raised points to the depth of the web. Typically, only 10-25% of the surface available for bonding is converted to fused, compacted areas of bonding. Optimum conditions of pressure and temperature depend on many variables, including the nature of the web, line speed, and the engraved pattern. Even small changes can result in significant changes in the structure and properties of the bonded web.

To achieve good properties with the retention of optimum hand/feel in the final fabric, it is essential that the surface temperature of the calendar rolls be selected appropriately. It has been shown that both strength and elongation increase with bonding temperature and then decrease after an optimal value [Zhang et al 1997, Nanjundappa and Bhat, 2005, Bhat and Kotra 2008]. The initial increase in the properties is due to good fiber-to-fiber bonding with increase in temperature till the optimum. Excessive heat can cause over bonding and alter the material characteristics. The optimum bonding temperature depends on the fiber morphology and the fabric structure. Under similar bonding conditions, the bonding patterns differ substantially depending on the fiber morphology. Bonding conditions will have to be modified to

accommodate different conditions of fiber spinning. For example, increasing the rate of polymer throughput when a fabric with a certain basis weight is produced necessitates an increased line speed.

In this research, an in-depth investigation has been done to understand the bond structure, especially to examine bond thickness and its cross sections at various bonding conditions. The relationship between the bond structures and the tensile properties is elucidated.

Sample Preparation and Characterization

The webs were prepared at the Textiles and Nonwovens Development center (TANDEC) at the University of Tennessee, Knoxville using the modified Reicofil-1 spunbond line. Polypropylene polymer supplied by Exxon Mobil Corporation with a melt flow rate of about 35g/10mproduced by Ziegler Natta polymerization method was used. The fiber diameter was maintained in the same range (about 19 microns) for different throughputs by appropriately adjusting the process conditions and two basis weights, 35 and 70 g/sq.m (gsm) were produced. The bonding temperature was varied over a range and the pressure was kept the same for a basis weight. For 35 gsm webs, bonding temperatures of 120, 131 and 149^{o}C were used and for the 70 gsm web, temperatures of 120, 140 and 149^{o}C were used. These temperature ranges were selected based on our earlier studies [Nanjundappa and Bhat, 2005]. These three different bond temperatures were selected to have low, optimum and over-bonding and the temperatures were different for the samples with different basis weight to achieve desired bonding. The calendar pressure used was 53.6 kg/cm and 71.5 kg/cm for 35gsm and 70gsm webs, respectively. Since the optimum bonding temperature is different for the two fabrics due to their mass difference, the middle value of the temperature, which is the optimum based on tensile properties showing combination of high tensile strength and elongation with high energy to break, is different for the two samples.

Thickness and tensile properties of the webs were measured according ASTM standard [ASTM, 2003]. The fabric samples were tested on the United Tensile Tester to determine the tensile properties. The fabrics were cut with a template measuring 25.4*2.54 cm^2 (10*1 inch^2) along the machine direction and the cross direction. The gauge length used was 12.7 cm (5 inch) and the extension rate, 12.7 cm/min (5 inch/min). Single bonds were tested by taking a strip of fabric about 80mm*5mm and cuts were made across the width of the fabric in such a way that the two pieces are held together by a single bond point. The cuts were made very close to the periphery of the bond. This was tested on a United Tensile Tester with a gauge length of 2.54cm (1 inch) and crosshead speed of 1.27cm/min (0.5 inch/min).

The Hitachi S-3000 Variable Pressure scanning electron microscope (SEM) was used to obtain the images of the bonded fabrics and the specimens after tensile testing. Charging is controlled in this instrument by using high vacuum. The back-scattered electrons collected by the Back Scatter Detector in topographic mode were analyzed. Secondary electrons could not be utilized to produce the image due to the partial gas pressure in the sample chamber. Images were captured from both the engraved calendar side and the smooth calendar side of the fabric. The excitation voltage and the gas pressure were kept constant at 25KeV and 30Pa respectively. Ruptured samples from fabric tensile testing were used to study the effect of increasing stress on the bond points and the fibers bridging the bonds. Successive images were obtained from the point where the fabric was clamped between the jaws in the tensile tester, towards the point where rupture occurred. Images were recorded from both sides of the fabric. Some of the photographs of the bond surface and cross sections were obtained using the SEM at the Air Force Research Laboratory at Edwards AFB, CA.

Results and Discussion

Tensile Properties and Failure Mechanisms

The tensile properties of the fabric are affected by the filament properties, orientation of the fibers in the web, and the bonding conditions. The bonding conditions including calender temperature, calender pressure and contact time seem to have the greatest effect on the tensile properties. As reported before, when bonding temperature is increased, with constant throughput and basis weight, it is seen that peak stress increases till it reaches a peak value and then declines [11]. The same trend is seen for peak extension as well. The main contributor to this observed trend is the manner in which the filaments bond together in the bond area. Increase in fabric weight requires increased bond temperature, contact time and nip pressure to attain optimum transfer of heat and to produce a fabric with optimum properties.

Representative stress-strain behavior of spunbond fabrics bonded at three different temperatures is shown in Figure 1, which shows a 35 gsm sample and the results are quite similar to the webs of 70gsm as well. There is distinct difference in the strength, modulus and elongation of the fabrics that are under-, optimum- and over-bonded. Although these look like extreme cases, in many instances, the temperature differences are less than 10°C. That is why it is important to understand the mechanism of bond failure and the reasons for observed failure modes.

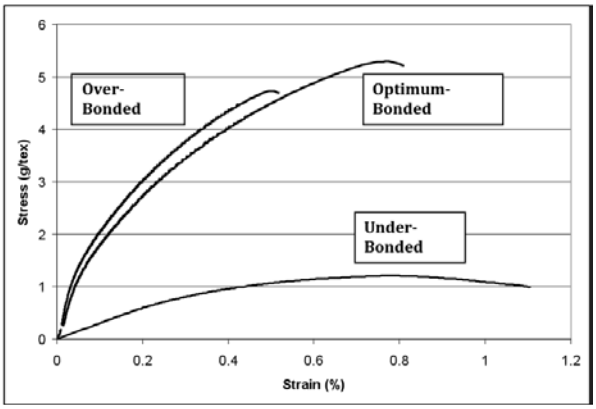


FIG. 1 STRESS-STRAIN PROFILE OF 35 GSM THERMAL BONDED WEBS BONDED TO DIFFERENT EXTENT

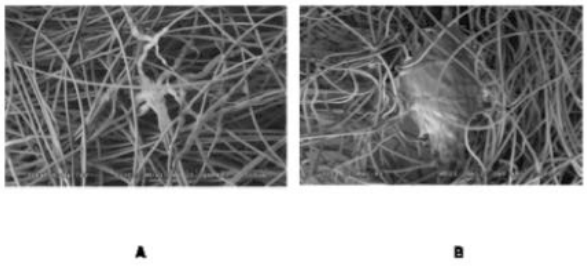


FIG. 2 SEM PHOTOGRAPHS OF BONDS DURING (AFTER OR DURING TENSILE TEST!), TENSILE DEFORMATION: UNDER-BONDED WEB (A) AND OVER-BONDED WEB (B) FOR THE 35 GSM FABRIC

Considering the extremes of samples, webs bonded at low bonding temperatures or short contact times, have similar bond areas, and the mode of rupture proceeds via disintegration of the bond area. As higher stress is encountered, filaments 'peel off' from the bond until the entire bond disappears as seen in figure 2A. In the bond areas, the fibers that are typically round in cross section are deformed into flat ribbon shapes observed under higher magnification. Final rupture takes place when these filaments break. These samples characteristically exhibit low peak stress and high breaking strains.

The other extreme is the samples bonded at high bonding temperatures. In this case, the bond areas are strong due to larger areas of bonding between the individual filaments. The higher temperatures or higher contact times that produce such bonds also cause the bond peripheries to be weaker. The bond periphery in this case will be expected to have polymer that is squeezed out of the bond by the lands of the calender, which would have solidified under conditions of no tension. The bridging filaments between the bonds have progressively lower extension, which affects the load sharing between the filaments and causes it to rupture earlier as seen from figure 2B. Such a phenomenon has been observed by other researchers as well [Wang and Michielsen, 2001].

The optimum tensile property samples rupture due to filament separation from the bond areas, but the bond itself is deformed first, and the bond disintegration occurs later (figure 3) at a higher stress level compared to that in the sample bonded at lower bonding temperatures. Some points of rupture also occur at the bond periphery. Due to the combination of stronger bond and extension of the bonds before disintegration, the samples exhibit the highest breaking load and higher values of peak elongation.

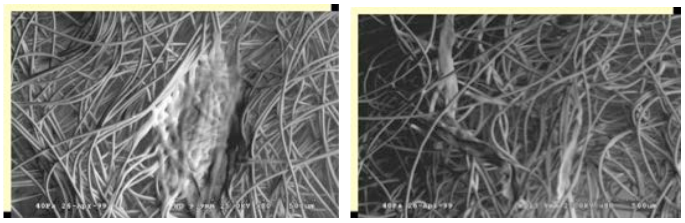


FIG. 3 SEM PHOTOGRAPHS OF AN OPTIMUM BONDED 35 GSM WEB DURING TENSILE DEFORMATION: INITIAL STAGES (A) AND CLOSE TO FAILURE (B)

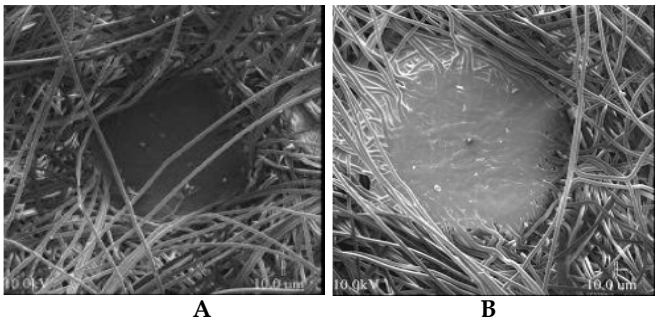


FIG. 4 TOP (A) AND BOTTOM (B) SURFACE OF THE BOND AREA OF A SPUNBONDED PP FABRIC (35 GSM, 131 ^{O}C)

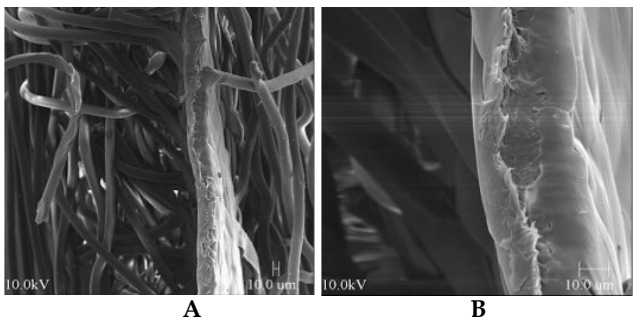


FIG. 5 CROSS SECTIONAL VIEWS OF THE BOND AREA (A) AND THE BOND AT HIGHER MAGNIFICATION (B) - (35 GSM, 131 ^{O}C)

The tensile properties of the fabrics produced at different bonding temperatures for fabrics of two different weights are shown in Table 1. For both sets, the tensile strength and elongation show a pattern of increasing with bonding temperature and dropping off with over-bonding. Only the modulus values continue to increase as the web becomes stiffer with bonding. The strength and modulus are normalized with respect to fabric weight for comparison. Strength and modulus values are in the same range for both fabrics, and breaking load is higher for the heavier fabric. The peak elongation values are slightly different for the two fabrics showing more dramatic effect for lighter weight fabric with bonding temperature. This is also reflected in breaking energy value changes. Breaking energy is a good indicator of bonding performance. Breaking energy values show a big drop in value with over bonding, which is only 9°C above the optimum temperature as observed in this study. This observation indicates that a small change in bonding temperature will have a large impact on the performance of thermal bonded webs.

Bond Structure

Observation of the bond areas with the help of a scanning electron microscope yielded important information about the nature of bonding between filaments. The effect of bonding temperature seems to have an overriding effect on the differences in filament properties in determining the nature of the bond. With increase in bonding temperature, the filaments in the bond area gradually lose their round shape and become more flattened. This leads to a greater surface area of the filament participating in the bond to make it more coherent. Increasing the contact time in the calender nip also causes the filaments to flatten out.

TABLE I TENSILE PROPERTIES OF DIFFERENT SPUNBOND FABRICS

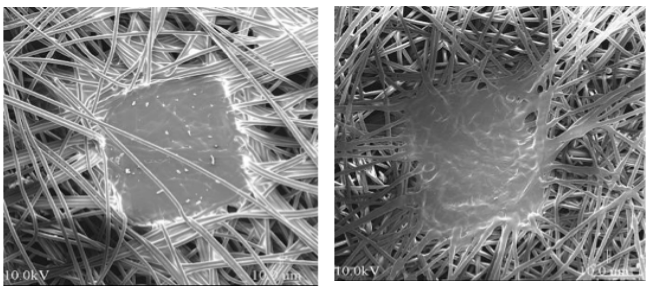
Sample	Peak Stress g/tex	Peak Elongation %	Initial Modulus, N/tex)	Breaking Energy, Kg-m
35 gsm/ 120 °C	3.9	112	0.18	0.41
35 gsm/ 131 °C	6.6	176	0.25	0.86
35 gsm/ 149 °C	1.9	12	0.28	0.03
70 gsm/ 120 °C	2.3	35	0.18	0.19
70 gsm/ 140 °C	6.1	129	0.28	1.40
70 gsm/ 149 °C	3.2	30	0.35	0.19

Top and bottom surfaces of a typical bond are shown in Figure 4, and the cross sectional views of the bonds in figure 5. From both top and bottom views, it is clear that the filaments are flattened well and a good bond is formed. There is not much difference in the bond area part of the fabric in the two sides. The cross sectional photographs clearly indicate that a good bond is formed with significant flattening and packing of the filaments.

TABLE II FABRIC AND BOND THICKNESS FOR THE SPUNBOND SAMPLES

Sample	Web Thickness, microns	Bond Thickness, microns
35 gsm/ 120 °C	165	30
35 gsm/ 131 °C	171	25
35 gsm/ 149 °C	180	33
70 gsm/ 120 °C	317	50
70 gsm/ 140 °C	333	45
70 gsm/ 149 °C	320	55

The packing of fibers in the bond area is quite similar for different bonding temperatures as well. The differences in bond thickness values estimated based on the SEM photographs do not show any trend and they are all in the same range for different bonding temperatures. That is why there is little difference in thickness of the bond with bonding temperature. However, the definition of the bond changes as shown in Figure 6. The flow of molten polymer away from the bond is evident for samples bonded at higher temperatures. This phenomenon explains the reasons for structural differences in the bond periphery, which leads to failure at lower level of elongation. Similarly, based on bond thickness, it is apparent that the density of the fabric increases from 0.20 g/cc in the unbonded web to almost 1.1 g/cc, if it is assumed that the weight is same, which is not possible since the PP density is only about 0.95 g/cc. This further explains that some of the fiber mass is expelled out of the bond area during the point bonding process.



A **B**

FIG. 6 TOP SURFACE OF THE BOND POINTS FROM FABRICS BONDED AT LOW OR OPTIMUM TEMPERATURE (A) AND AT VERY HIGH TEMPERATURE (B) - (35 GSM, 131 ^{O}C)

Summary

It has been very well known that the tensile properties change rapidly with change in bonding temperature during thermal bonding, for both spunbond and staple fiber webs. The analysis of the failure mechanisms helps us understand the translation of change of process conditions into changes in fabric tensile properties. It was clearly shown that failure mechanisms are different for under-bonded, over-bonded and optimum-bonded fabrics. The optimum bonding temperature is dependent on the fiber morphology as well as the web weight and line speed. By selecting appropriate bonding conditions, based on fiber morphology and basis weight, it should be possible to produce fabrics with the desired tensile properties. The thickness of the bond was about one sixth of the web thickness in most of the cases. Although bond thickness showed only small changes with bonding temperature, the bonding temperature affected the interfiber fusion and flow of polymer within and out of the bond, thus affecting the failure mechanism.

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